A Preliminary Evaluation of the Potential Downstream Sediment Deposition Following the Removal of Iron Gate, Copco, and J.C. Boyle Dams, Klamath River, CA

Final Report

Prepared for

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May, 2004

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1 Introduction

In December 2003, Stillwater Sciences was commissioned by American Rivers, Trout Unlimited, California Trout, and Friends of the River to conduct a preliminary assessment of the sediment transport characteristics in the Klamath River. This assessment used Stillwater Sciences' Dam Removal Express Assessment Model, DREAM-1, to simulate the removal of Iron Gate, J.C. Boyle, and the two Copco dams (shown in Figures 1a, 1b, and 2).

Stillwater Sciences was contracted to provide a first-order, rapid assessment of sediment deposition downstream of Iron Gate Dam and whether this deposition would significantly alter floodplain inundation during high flows following the removal of Iron Gate, J.C. Boyle, and the two Copco dams. Due to limited resources and a tight schedule, no new data were collected and the evaluation was based solely on available information. Because there are not sufficient data available, the degree to which suspended sediment concentration will be elevated, which is one of the major biological concerns in many dam removal projects, cannot be accurately assessed at this time. In addition, overbank sediment deposition and fine sediment infiltration into gravel interstices are not evaluated.

The sediment transport model used in the evaluation, DREAM-1, is a one-dimensional sediment transport model designed to assess sediment transport and deposition following dam removal for reservoir deposits primarily composed of sand. It can also predict suspended sediment concentrations if erosion of reservoir sediment is governed by the transport of non-cohesive coarse sediment (sand and coarser). Details of the sediment transport model, DREAM-1, can be found in Cui et al. (in press [a, b]), and are not discussed further here. The majority of the sediment in the Klamath River reservoirs, however, is silt and clay (as discussed below), and thus, it is likely that the erosion of reservoir sediment will be governed by the cohesiveness of the sediment in addition to the transport capacity of coarse sediment. Although DREAM-1 can be easily modified to accommodate the erosion of cohesive sediment, application of such a modified model would require additional field data, which are not available at this time and cannot be collected without additional resources. With that, this study focuses on the deposition of sediment downstream of the dam within the main channel, first by calculating shear velocity relative to settling velocity followed by numerical simulation with standard engineering approaches. In particular, the cohesiveness of the reservoir sediment deposit is neglected in the numerical simulation. Because the cohesiveness of the sediment deposit holds sediment particles together and resists their entrainment, the simulation overestimates the rate at which the reservoir deposit would be released. In addition, the simulation applies safety factors to estimate the amount of sediment deposited in the reservoirs, to ensure that the amount of modeled sediment release downstream following dam removal will not be underestimated. The combination of a higher rate of sediment release than is likely by neglecting cohesiveness of sediment deposit and the application of safety factors in total volume of sediment released results in a worst-case-scenario prediction in terms of the magnitude of sediment deposition downstream of the dam.

A one-day field reconnaissance trip was conducted prior to the modeling exercise to familiarize Stillwater Sciences staff with the project and the relevant issues. No field data were collected during the field reconnaissance.

This study assumes that J.C. Boyle and Copco dams will be removed first before the removal of Iron Gate Dam to try to minimize downstream impacts. The simulated reach includes Iron Gate Reservoir and the entire mainstem Klamath River downstream of Iron Gate Dam.

2 Geology, Geomorphology, and Hydrology of the Klamath River Basin

The geology of the Klamath River near Iron Gate Dam is made up of Western Cascade Volcanic rocks upstream of the confluence with Cottonwood Creek (at RM 182.2), with High Cascades volcanics in the uplands, particularly upstream of Copco Dam. High Cascades volcanic terrains are typified by very low sediment supply rates, spring-dominated streams, and low drainage densities. Downstream of Cottonwood Creek, bedrock geology consists of Mesozoic metamorphic rocks.

The hydrology of the Klamath River is altered by dams and water diversions (Figures 1a and 1b). There are five hydropower and flow regulation dams operated by PacifiCorp (Table 1), and Link River Dam (located at the outlet to Upper Klamath Lake) is operated by the US Bureau of Reclamation for local water supply and hydropower generation.

Table 1. Klamath River dams operated by PacifiCorp (source: PacifiCorp 2003).

Dam	**Location (river mile)**	**Year completed**	**Reservoir capacity (acre-feet)**	**Normal active storage capacity (acre-feet)**
Iron Gate Dam	190.1	1962	58,794	3,790
Copco 2	198.3	1925	73.5	n/a
Copco 1	198.6	1918	46,867	6,235
J. C. Boyle	224.7	1958	3,495	1,724
Keno	230.3	1967	18,500	n/a

The longitudinal profile of the Klamath River downstream of Iron Gate Dam is shown in Figure 3. The channel gradient averaged over one-mile distances for the same reach is shown in Figure 4, which is derived from a large scale plot in Ayres Associates (1999). The average channel slope downstream of Iron Gate Dam is 0.0025, and does not vary significantly above RM 50.

The Klamath River is dominated by plane-bed morphologies from Iron Gate Dam downstream to RM 179, and becomes dominated by pool-riffle morphologies farther downstream (PacifiCorp 2003). Upper Klamath Lake is a natural lake that historically trapped all of the coarse (sand and coarser) and most of the fine sediment supplied from the upper Klamath River basin. Coarse sediment (sand and coarser) in the reservoirs and the Klamath River downstream of Iron Gate Dam originates from tributaries downstream of Upper Klamath Lake. Downstream of Iron Gate Dam, sediment in the channel has a median size (D_{50}) of approximately 100 mm (Figure 5). The bed fines near the confluence of Bogus Creek (the first tributary downstream of Iron Gate Dam), and continues to fine with the input of tributaries. Downstream of Cottonwood Creek, there are no clear trends in D_{50} until the confluence with the Scott River (PacifiCorp 2003). Detailed results of pebble count data downstream of Iron Gate Dam are given in PacifiCorp (2003).

3 Sediment Deposit in the Reservoirs

There has been no systematic coring of the sediment deposits in any of the reservoirs. Eilers and Gubala (2003) conducted bathymetric surveys in Keno, J.C. Boyle, Copco, and Iron Gate reservoirs in fall 2001. During the bathymetry study, Eilers and Gubala (2003) also estimated the volume fractions of different classes in each reservoir, as shown in Table 2 (see also PacifiCorp 2003). The pre-dam topography in the reservoir area used for their assessment of stored sediment volume does not include the area within the original bankfull channel (Eilers and Gubala 2003, PacifiCorp 2003). The lack of information regarding storage within the bankfull channel may result in significant error in estimating the amount of sediment to be released because all of the sediment within the original bankfull channel is likely to be released following the removal of the dam, despite the high likelihood that it constitutes only a small portion of the total sediment deposit. The sediment composition in each reservoir was estimated based on 30 sediment samples collected within the above reservoirs, including one in Keno Reservoir, 4 in J.C. Boyle Reservoir, 18 in Copco Reservoir, and 7 in Iron Gate Reservoir (Eilers and Gubala 2003, PacifiCorp 2003). Because Western Cascade Volcanic geology yields primarily fine sediments, and Upper Klamath Lake and Lake Ewauna trap coarse sediment (sand and coarser) in the main stem Klamath River immediately upstream of Keno Reservoir, the sediment deposits in Keno, J.C. Boyle, Copco, and Iron Gate reservoirs contain a very small proportion of coarse sediment. In Keno, J.C. Boyle, Copco, and Iron Gate reservoirs, the proportion of material sand-sized and coarser was approximately 32%, 20%, 1%, and 20%, respectively (Eilers and Gubala 2003, PacifiCorp 2003). The remainder of the sediment in these reservoirs was silt and clay (Eilers and Gubala 2003, PacifiCorp 2003). Sediment stored in Copco II reservoir is ignored in this study due to its extremely small size. Assuming the above sediment composition is accurate, the estimated sediment volumes by composition in each reservoir are given below in Table 2.

Table 2. A rough estimate of sediment deposit by composition (in yd^3) in the four reservoirs in the Klamath River, based on data from PacifiCorp (2003)

	Sand and Coarser	Silt and Clay	All Sediment
Keno	46,000	98,000	144,000
J.C. Boyle	4,000	18,000	20,000
Copco	104,000	10,267,000	10,370,000
Iron Gate	963,000	3,852,000	4,810,000
Total	1,117,000	14,235,000	15,344,000

The amount of the sediment deposit that can be eroded and transported downstream following the removal of the dams will be estimated later in Section 4.3 based on the information provided by Eilers and Gubala (2003) and PacifiCorp (2003), given above in Table 2.

4 Input Data to DREAM-1

Data required for input to the model include discharge records, a longitudinal profile through the reservoir area and downstream of the dam, channel width measurements downstream of the dam, surface composition (e.g., grain size distribution and bedrock control) downstream of the dam, and the volume, spatial distribution, and grain size distribution of the reservoir deposit.

4.1 Discharge

Daily average discharge records downstream of the dam are required as input to DREAM-1, which uses available data at different locations to account for the change in discharge due to the contributions from tributaries. DREAM-1 assumes that the hydrologic record is indicative of hydrology following dam removal. The period of record and the location of available gauges on the Klamath River downstream of Iron Gate Dam are given in Table 3.

Table 3. Available daily average discharge record on the Klamath River downstream of Iron Gate Dam

Site number	Site name	Period of record
USGS 11516530	Klamath River below Iron Gate Dam, CA (RM 190)	10/01/1960 – 09/30/2002
USGS 11520500	Klamath River near Seiad Valley, CA (RM 129)	10/01/1912 – 09/30/2002
USGS 11523000	Klamath River at Orleans, CA (RM 60)	10/01/1927 – 09/30/2002
USGS 11530500	Klamath River near Klamath, CA (RM 5)	10/01/1910 – 09/30/2002

In order to increase the accuracy of the model results, the period of each hydrologic record used in the model must be the same, so that each gauge records data with the same climatic inputs. Table 3 shows that the period of record for all four gauges extends through 2002. The shortest daily average discharge record for the four stations is the Klamath River below Iron Gate Dam gauge, which starts in WY 1961 (10/1/1960 – 9/30/1960), and thus, the hydrological records needed for input to the model for all four stations will encompass WY 1961–2002. Before applying the hydrologic record from WY 1961-2002 to the model for dam removal simulation, we must assess whether the discharge in the period of WY 1961–2002 differs significantly from that following the removal of the dams when the flow regulation from the reservoirs slated for removal ceases. There are only 5–7 years of discharge data at two stations prior to the completion of Copco Dam in 1917, which is not sufficient to assess the role of Copco Dam on hydrology in the Klamath River. Copco Reservoir, however, was constructed for power generation purposes with an active storage capacity of 6,235 acre-ft (or 0.4% of the long-term annual run-off) and does not bear flood control responsibilities, and thus its influence on discharge should be minimal. Comparison of the discharge record before and after the construction of Iron Gate Dam at the Klamath River below Iron Gate Dam gauge (USGS #11520500), as shown in Figure 6, indicates that the operation of Iron Gate Dam did not significantly alter the flow duration, particularly the high-flow events. With that, we assume that the post-dam-removal hydrological condition would be similar to the hydrological records between WY 1961 and 2002, and we selected typical hydrological conditions from those water years for the numerical simulation.

It is likely that the hydrological conditions immediately following the removal of the dams would significantly affect sediment erosion in the reservoir area and sediment transport conditions downstream of the dams. According to the sensitivity tests conducted by Cui and Wilcox (in press) and Cui et al. (in press [a,b]), high flow conditions help to flush the sediment out of a reservoir more quickly, and thus reduce the duration of sediment transport impact from dam removal. Low flow conditions, on the other hand, elongate the sediment transport process but reduce the magnitude of sediment deposition and suspended sediment concentration downstream of the dam (e.g., Cui and Wilcox, in press; Cui et al., in press [a,b]). Thus, three representative water years were selected from the period of WY 1961–2002 based on daily average discharge record at Klamath River below Iron Gate Dam (USGS # 11516530). The discharge records for the selected three years represent a wet year with exceedance probabilities for peak flow and annual run-off at approximately 10%, an average year with exceedance probabilities for peak flow and annual run-off of approximately 50%, and a dry year with exceedance probabilities for peak flow and annual run-off of approximately 90%. The selected typical water years are given in Table 4, and the daily average discharge records for the three years are shown in Figure 7.

Table 4. Typical water years selected for dam removal simulation, based on USGS #11516530

Type	Water year	Peak flow (cfs)	Annual run-off (acre-ft)	Exceedance probability (%)	
				For peak flow	**for annual run-off**
Wet	1972	17,000	2,332,000	9	12
Average	1976	5,900	1,497,000	49	58
Dry	1991	2,430	700,000	93	91

In general, sediment transport capacity in a dry water year is relatively small, and thus will result in relatively slow sediment release from a reservoir deposit. As a result the magnitude of sediment deposit downstream of the dam site may be slightly smaller. Because of the relatively small sediment transport capacity, however, the downstream sediment deposit will stay in place for a longer period of time. A wet year, on the other hand, will usually result in slightly thicker downstream sediment deposition that persists for a shorter period of time due to the faster release of reservoir sediment. Thus, simulation with the dry year scenario represents the condition under which there is approximately 10% probability that the duration of downstream sediment deposition will be longer than simulated; and simulation with the wet year scenario represents the condition under which there is approximately 10% probability that the downstream sediment deposition is thicker than predicted. The simulation applied either the dry year (1991) or the wet year (1972) as the first year, while the average year (1976) was used for the second year for the simulation. It turns out, based on the model simulations presented later, there would be no significant aggradation after the first 18 months.

4.2 The longitudinal profile and bankfull channel width of the river

The longitudinal profile downstream of Iron Gate Dam shown in Figure 3 was used as input to the model. There is not sufficient information to derive detailed historical longitudinal profiles upstream of Iron Gate Dam. Here, the reservoir bathymetry data presented in Eilers and Gubala (2003) and PacifiCorp (2003) is used to derive a longitudinal profile, as shown in Figure 8. Note that the bathymetry in PacifiCorp (2003) includes the reservoir sediment deposit. This post-dam profile is used as a surrogate for the historical longitudinal profile without subtracting the thickness of sediment deposit for the following reasons: (1) The sediment deposit is likely to be relatively thin (discussed in detail in Section 4.3 below), and its exact thickness and spatial distribution is not known; (2) the derived longitudinal profile contains relatively large errors (which involves reading elevation data from a small-scale 10-ft interval contour map), and it is likely that this error is larger than the adjustment in thickness; and (3) using the current longitudinal profile as a substitute for the historical profile will result in a slightly faster sediment release due to the slightly steeper assumed slope. The sediment deposit as discussed in Section 4.3 will be added on to this longitudinal profile. This assumption itself does not increase the volume of the sediment deposit because the pre-dam longitudinal profile is assumed to be fixed and cannot be eroded.

Bankfull channel widths were measured from 1998 1:7,500-scale orthorectified aerial photographs, and then interpolated to the 1-mile spacing to be used in the modeling, as shown in Figure 9. Based on the reconnaissance visit, it was determined that the vegetation along the channel margins was a reasonable indicator of bankfull width. Field observation also indicates that the river banks are rather steep, and thus using the vegetation as the indicator for the bankfull boundary will result minimal error even if it is grown at an elevation slightly lower than bankfull.

4.3 Spatial distribution of reservoir sediment deposits

Because the sediment deposits are relatively wide, not all of the sediment in the reservoir deposits will be eroded and transported downstream. The actual amount of the reservoir deposit that will be eroded following the removal of a dam depends on many factors including: the topography of the reservoir area, the spatial distribution of the reservoir deposit, the grain size distribution and other physical characteristics of the reservoir deposit, and the rate at which the reservoir water would be drawn down following the dam removal, among other factors. When a dam is built and the reservoir water surface begins to rise as water storage increases, the river will lose part or all of its sediment transport capacity, beginning at the tail water zone (the upstream extent of the backwater from the reservoir). Typically, coarse sediment that is transported as bedload will deposit first near the upstream end of the tail water zone to form a depositional delta, while the suspended finer particles continue to travel downstream and settle in deeper water, as shown in the sketch in Figure 10. One of the characteristics of the coarse sediment deposit in the delta is that water depth over the delta area lacks much longitudinal variation. It is expected that the coarse sediment would fill in the main channel first and then expand laterally, forming a fan deposit as shown in the sketch in Figure 11 (a).

The fine sediment deposit, on the other hand, is expected to be more laterally uniform because the water velocity in the deep portions of the reservoir is very small and sediment is distributed laterally via diffusion, as shown in the sketch in Figure 11 (b). The deposits in Copco and Iron Gate reservoirs contain primarily fine sediment (Table 2), and thus it can be expected that the spatial distribution of their reservoir deposits are relatively uniform. Because both Copco and Iron Gate reservoirs get continuously deeper in the downstream direction, typical of a reservoir deposit consisting of fine rather than coarse sediment (as discussed earlier in this section), it is likely that neither reservoir contains a large coarse sediment delta, although a small one toward the tail of each reservoir is possible. It needs to be stressed that the above analysis is only based on general scientific understanding of sediment deposition processes in reservoirs, and an understanding of the detailed spatial distribution of reservoir deposit in the Copco and Iron Gate reservoirs can only be acquired through more detailed field measurements.

DREAM-1 assumes that following dam removal, the Klamath River would carve a channel with a trapezoidal cross section (shown schematically in Figure 12), and the maximum amount of sediment that can be eroded and transported downstream is a function of the thickness of sediment deposit in the main channel (i.e. thickness over the pre-dam channel bed). Given that the original Klamath River valley topography appears to be visible in Iron Gate and Copco reservoirs, as shown in Figures 13 and 14, it is likely that the flow would recover the old Klamath River channel following removal, rather than erode into lateral sediment deposits. With this assumption, the channel is not expected to meander through the reservoir deposit and erode significantly more sediment than the volume necessary to create a single channel. Any potential sediment release from erosion of lateral sediments outside the single channel was accounted for in the modeling using safety factors, as discussed below.

Because the exact thickness of the sediment deposits in the main channel area of the Klamath River in Copco and Iron Gate reservoirs is unknown, we used safety factors to greatly reduce the likelihood that the amount of sediment released in the simulation would be less than the actual amount of released sediment. Detailed field data would be required to more accurately assess the volume of sediment that would be released following the removal of the dams.

The first step in assessing the thickness of the deposit behind Iron Gate Dam is to calculate the average thickness of the reservoir deposit if it were spread throughout the reservoir. The depositional area of Iron Gate Reservoir is approximately 75,000,000 ft^2, as shown in Figure 13. Distributing the 4,810,000 yd^3 of sediment uniformly into a 75,000,000 ft^2 area results in an average thickness of sediment deposit of about

1.73 ft in Iron Gate Reservoir. It should be noted that the 1.73 ft calculated above is only an average thickness of sediment deposit in Iron Gate Reservoir and is not the thickness to be used for the simulation.

This thickness would be greater if the upstream dams (Copco, Copco 2, and J.C. Boyle) were also removed. Due to the relatively small volume of sediment in J.C. Boyle and Copco 2 reservoirs, only the sediment deposit in Copco Reservoir is considered in this analysis if the other dams will be removed before the removal of Iron Gate Dam. There is 10,370,000 yd^3 of sediment deposited in Copco Reservoir with an estimated depositional area of approximately 32,000,000 ft^2, as shown in Figure 14. Assuming that the sediment is uniformly distributed in the reservoir, the average thickness of sediment deposition would be 8.75 ft. Following the removal of Copco Dam, the flow would carve a channel similar in size to the pre-dam channel, which has an average width of approximately 150 ft. It needs to be noted that, in the numerical model, the channel that carves into the reservoir deposit is assumed to be trapezoidal with bank slopes equal to the angle of repose, but for the rough estimates here it is assumed to be a simple rectangle. If we multiply the width of the channel by the average sediment depth and the length of the reservoir (4 miles), there would be approximately 1,027,000 yd^3 of sediment released downstream to Iron Gate Reservoir. Again, we do not know exactly how the sediment is distributed in Copco Reservoir, and the above assumption may underestimate the amount of sediment released downstream following the removal of Copco Reservoir. As a safety precaution, here we assume that 5 times of this amount will be released, i.e., the average thickness of sediment deposit to be released is 43.75 ft, and the volume of sediment to be released to Iron Gate Dam following the removal of the Copco Dam is 5,135,000 yd^3, which is approximately half of the sediment deposit in the Copco Reservoir. Given that the average width of sediment deposition zone in Copco Reservoir is more than 1,500 ft, and the active channel width is only about 150 ft, this is probably a huge overestimate. The conceptual model of Doyle et al. (2003), as shown in Figure 15, for example, indicates that, although the channel eroded through the reservoir deposit may temporarily widen (stage E in Figure 15), this temporary width increase is not significantly wider than its final form (stage F in Figure 15). Field observations following dam removal in Clear Creek, California, and dam collapse in Town Creek, California, shown in Figures 16 and 17, respectively, also suggest that the channel width carved in the reservoir deposit will be similar to the stable channel width downstream of the dam.

Adding the 5,135,000 yd^3 of potentially mobile Copco Reservoir sediment to Iron Gate Reservoir results in an additional average depositional thickness of 1.85 ft.

Similar to the analysis of sediment release from Copco Reservoir, a safety factor was used to make it highly unlikely that the sediment release from Iron Gate Dam is underestimated. The estimated amount of sediment release from both Copco and Iron Gate reservoirs are given in Table 5.

Table 5. Estimate of depositional thickness in Iron Gate Reservoir

	Copco	**Iron Gate only**	**Copco release plus Iron Gate sediment in Iron Gate Reservoir**
Total volume (yd^3)	10,370,000	4,810,000	9,943,000 (= 5,135,000 + 4,810,000)
Depositional area (ft^2)	32,000,000	75,000,000	75,000,000
Thickness (ft)	8.75	1.73	3.58 (= 1.85 + 1.73)
Safety factor	5	5	5
Estimated width (ft)	150	150	150
Estimated length (mile)	4	6.5	6.5
Estimated sediment release (yd^3) if deposits are uniformly distributed	1,000,000	330,000	680,000
Estimated sediment release (yd^3) with safety factor to be used in the model	5,100,000*	1,600,000*	3,400,000*

It is important to stress that the safety factors used above are very conservative (i.e., they may significantly overestimate the volume of sediment that will be supplied to downstream reaches, so that the depositional thickness predicted by the model will be greater than we would expect). This can be illustrated by comparing the volume of sediment we expect to be released based on the expected channel width and the amount of sediment used in the model. For Copco Reservoir, the assumed amount of released sediment is approximately 50% of the sediment deposit, where the ratio of the depositional width of the reservoir to the active channel width is about 10 (i.e., only 1/10 of sediment would be released if the sediment is deposited uniformly across the reservoir bottom rather than the 1/2 that the model uses). For Iron Gate Reservoir, the assumed amount of released sediment is approximately 34% of the total amount of sediment in Iron Gate Dam and the estimated amount of sediment from Copco Reservoir combined. The average width of sediment deposition in Iron Gate Reservoir is approximately 2,300 ft, and following dam removal the active channel would be approximately 150 ft wide (i.e., the depositional width to active channel width ratio is approximately 15, and only 1/15 of sediment will be released if the sediment is deposited uniformly rather than the 1/3 of the sediment used in the model).

Longitudinally, it is assumed that the upstream end of sediment deposit in Iron Gate Reservoir is located 6.5 miles upstream of Iron Gate Dam. The sediment is assumed to be deposited in Iron Gate Reservoir as a triangular wedge, with the thickness of the deposit being twice of the average thickness (with the safety factors) near the dam and zero at the far upstream end, i.e., the thickness of sediment deposit is 7.16 ft near Iron Gate Dam and 0 at 6.5 miles upstream of Iron Gate Dam, as shown in Figure 8. The hypothetical deposition profile shown in Figure 8 probably results in a significant overestimate of the volume of sediment that would be released following the removal of the dams, as discussed earlier. It also overestimates the thickness of sediment deposit near Iron Gate Dam, which also results in an overestimate of the sediment deposition downstream of the dam following dam removal, because the closer the sediment is to the dam, the more quickly it can be released following the removal of the dam. This is particularly true for coarse sediment (sand and coarser) in the reservoir deposit because the large lakes and reservoirs upstream intercept coarse sediment (sand and coarser), and most of the coarse sediment (sand and coarser) in the reservoir deposit is derived from the small tributaries, most of which feed directly into the reservoir areas. It can be expected that the coarse sediment (sand and coarser) derived from the tributaries accumulates in deltas where the tributaries enter the reservoir. These deltas may be located some distance away from the future main channel of the Klamath River, and thus sediment would be slowly metered out to the main channel as it moves down the tributary. As a result, the predictions of sediment deposition downstream of the dam are likely significantly larger than what would actually occur following the removal of the dams.

5 Numerical Simulation

5.1 Shear velocity vs. settling velocity calculation

In order to have a rough understanding of the potential sedimentation problems and to conduct the numerical simulation more efficiently, we conducted a shear velocity vs. settling velocity calculation to assess the potential risks of sediment deposition downstream of Iron Gate Dam. The analysis focuses on the particle grain sizes that would be transported as suspended sediment. Results of this assessment provided guidance to numerical simulation. For example, if the assessment indicated that the risk of significant sediment deposition downstream of Iron Gate Dam is extremely low (i.e., the majority of the sediment would remain in suspension under even low flows), it would be possible for us to use the low-resolution data available with adequate safety factors, so that the model will not likely under-predict the amount of sediment deposition following the removal of the dams. If the analysis indicated that the risks of significant sediment deposition downstream of Iron Gate Dam are high (i.e., sediment is unlikely to remain in suspension and may deposit on the channel bed) then there is considerably more uncertainty in the modeling results and more field data would need to be collected even for a preliminary assessment.

The Klamath River downstream of Iron Gate Dam is cobble-bedded with an average slope of about 0.0025 and relatively high discharge. The 2-year recurrence interval annual peak flow in the Klamath River downstream of Iron Gate Dam is close to 7,000 cfs (Figure 18), and the daily average discharge is higher than 3,000 cfs approximately 20% of the time (Figure 19). The simple exercise presented below can be used to estimate conditions necessary for sediment particles to be transported in suspension. This requires that shear velocity and particle settling velocity be estimated and compared. The shear velocity can be estimated with the following equations:

$$Q = \frac{1.49}{n} B h^{5/3} S^{1/2} \quad , \quad u_* = \sqrt{ghS} \tag{1a,b}$$

in which Q denotes discharge in cfs; n denotes Manning's n value; B denotes channel width in ft; h denotes water depth in ft; S denotes channel gradient; u_* denotes shear velocity in ft/s; and g denotes acceleration of gravity in ft/s^2. Assuming a channel gradient of 0.0025, a channel width of 150 ft, and a Manning's n value of 0.04, the shear velocity at discharges of 7,000 cfs and 3,000 cfs are 0.75 ft/s and 0.58 ft/s, respectively.

Figure 20 shows the particle settling velocity assessed using methods described by Dietrich (1982).

According to van Rijn (1984), sediment particles are likely to be suspended when

$$\frac{v_s}{\kappa u_*} < 1 \tag{2}$$

in which v_s denotes settling velocity; and κ is a constant with a value of approximately 0.4. Comparisons between shear velocity and settling velocity in Figure 20 indicate that sediment particles with a settling velocity of no more than 0.23 ft/s and 0.34 ft/s will likely be transported as suspended sediment downstream of Iron Gate Dam at a discharge of 3,000 cfs, and 7,000 cfs, respectively. This corresponds to sediment particles finer than 0.42 and 0.68 mm, respectively (Table 6). Although no detailed grain size analysis for the reservoir sediment has been conducted, it is expected, based on the analysis of Eilers and Gubala (2003) and PacifiCorp (2003), that the amount of sediment coarser than 0.42 and 0.68 mm (coarse sand) is very small. Given this result, we expect that most of the sediment in the reservoir deposit will be transported as suspended sediment even during relatively mild high-flow events, and thus significant fine sediment deposition within the main channel downstream of the dam will be extremely unlikely, although there will be unknown amount of fine sediment deposit along the banks, particularly where it can be trappd by riparian vegetation.

Table 6. An estimate of particle size that will be transported in suspension at 3,000 and 7,000 cfs.

Discharge	**3,000 cfs**	**7,000 cfs**
Shear velocity	0.58 ft/s	0.76 ft/s
Max. settling velocity for suspension	0.23 ft/s	0.34 ft/s
Corresponding particle size	0.42 mm	0.68 mm

5.2 Simulation strategy

DREAM-1 is designed for simulation of sediment transport following dam removal where the reservoir deposit is composed of primarily non-cohesive fine sediment (sand and silt). The reservoir deposits in the Klamath River are primarily silt and clay with only a small portion of sand (e.g., about 20% in Iron Gate Reservoir and about 1% in Copco Reservoir), and thus, it is very likely that the erosion of reservoir deposit will be governed by the cohesiveness of the sediment. For this reason, the sediment transport equation used in DREAM-1, Brownlie's bed material equation (Brownlie 1982), which was derived from data for non-cohesive sediment, may not be appropriate for simulating the erosion of the reservoir sediment. Instead, the approach and formulation of Partheniades (1962), which is designed exclusively for erosion and deposition of cohesive sediment, is likely more appropriate for quantifying reservoir erosion. Although modifying DREAM-1 to use the formulation of Partheniades (1962) to model reservoir erosion is a relatively easy task, its application requires the calibration of two parameters, the critical shear stress for erosion and the resuspension rate, using available field data. The required field data for quantification of the two parameters in Partheniades (1962) can be collected through reservoir drawdown experiments but are not available at this early stage of our analysis. The rate of reservoir erosion, and thus the magnitude of downstream sediment deposition will be greater if reservoir erosion is assumed to be governed only by the transport of sand and coarser material, as calculated with the Brownlie's bed material equation (Brownlie 1982). This is because the neglected cohesiveness of the fine sediment would have added additional resistance to erosion by the flow. Given the lack of required data, we can only evaluate the potential for sediment deposition downstream of Iron Gate Dam under the worst-case scenario assumptions. Results of this simulation, if in agreement with the shear velocity vs. settling velocity calculation, should contribute significantly to the dam removal evaluation process. The simulation with the likely worst-case scenario assumptions for downstream sediment deposition is presented below in Section 5.3.

5.3 Simulation of downstream sediment deposition with the worst-case scenario assumptions

The following assumptions were used to simulate the worst-case scenario in terms of downstream sediment deposition, given the available information regarding the size and distribution of reservoir deposits. Here, the worst-case scenario is defined based on the magnitude and duration of coarse sediment deposition in the main channel. As stated earlier, the duration and magnitude of increased suspended sediment concentration and turbidity levels cannot be modeled with existing information and are not considered.

- The thickness of the reservoir deposit available for erosion is 5 times the average thickness of the reservoir deposit for all reservoirs, as discussed earlier in Section 4.3. This ensures that the calculated volume of sediment released will not be underestimated.
- The fractions of coarse sediment (sand and coarser) in Iron Gate and Copco reservoirs are assumed to be 30% and 5%, respectively, which is higher than the preliminary assessment based on Eilers and Gubala (2003) (20% and 1%, respectively), by 50% for Iron Gate Reservoir and a factor of 5 for Copco Reservoir.
- The erosion of each reservoir deposit is governed by the transport of coarse sediment (sand and coarser) while fine sediment (silt and clay) is transported as throughput, and the presence of large fraction of silt and clay will not affect the rate of erosion.
- The sediment deposition is longitudinally distributed as a triangular wedge, as shown in Figure 8. In reality, the sediment is probably distributed farther upstream in the reservoir. Assuming that the majority of the sediment is deposited near the dam reduces the attenuation effect during transport through the reservoir area, and thus, the predicted sediment deposition downstream of Iron Gate Dam is likely higher than in reality.
- The grain size of the portion of the sediment deposit in the sand and gravel fraction is coarser than observed. The characterization of this portion of sediment in Eilers and Gubala (2003) only included sand (0.0625 – 2 mm), possibly due to the relatively small fraction of gravel. The assumed grain size distribution for sand and coarser particles in the reservoir deposit is given in Figure 21. It should be noted that the grain size distribution shown in Figure 21 is not based on field data but rather artificially constructed so that its median grain size is coarser than that in the actual reservoir deposit. For example, the median grain size distribution in Figure 21 is greater than 2 mm, coarser than the upper boundary for sand-sized sediment, and coarser than any of the material found by Eilers and Gubula (2003).

The model was run once with a dry water year (1991) and once with a wet water year (1972) to simulate the first year following dam removal. Simulation with the dry water year represents the condition under which there is approximately 10% probability that the duration of downstream sediment deposition will be longer; and simulation with the wet year represents the condition under which there is approximately 10% probability that the short-term magnitude of sediment deposition will be higher.

The following process is assumed for the removal of Iron Gate Dam in order to conduct the simulation:

- To use the low-level outlet to allow for reservoir draw-down during the base-flow season. A low-level outlet with invert elevation 2,185 ft exists on Iron Gate Dam. The outlet was originally used as diversion tunnel during dam construction and is equipped with a gate that can be partially opened. The discharge capacity for different water levels in Iron Gate Reservoir when the gate is fully open is given in Figure 22.
- Remove the dam above the water surface. Depending on whether the coffer dam upstream of Iron Gate Dam used for dam construction is still functional, most or all of the dam construction material could be removed above the drawn-down water surface. Other facilities such as the penstock and powerhouse would be removed during this time.
- Remove the underwater portion of the dam or coffer dam as quickly as possible to finish the dam removal. The low-level outlet would lose its function (i.e., become higher than water surface) as the reservoir level decreases with the proceeding of underwater excavation.

Four runs were conducted under the following assumptions:

- **Run 1.** The first run does not model dam removal. The low-level outlet on Iron Gate Dam will be used to release water and sediment indefinitely. The hydrologic sequences will follow a dry – average

– wet year series. The result of this run defines the form of sediment deposit after a period of reservoir draw-down with the outlet, and helps to determine when the dam should be removed.

- **Run 2.** Run 2 assumes that the dam is removed in a dry year, and the low-level outlet on Iron Gate Dam is used to release water and sediment for 6 months before the final removal of Iron Gate Dam. This run represents a realistic dam removal scenario under the worst-case scenario for downstream impact as defined earlier. The dry year used for simulation results in an overestimation of the period that a sediment deposit would persist downstream of the dam.

- **Run 3.** Similar to Run 1, Run 3 does not model dam removal and is designed to test the role of different hydrologic conditions using the low-level outlet. This scenario is identical to Run 1 except that a wet – average – dry series is used for simulation.

- **Run 4.** Run 4 is identical to Run 2 except that the dam is removed during a wet year. This run represents another realistic dam removal scenario under the worst possible conditions for downstream impact as defined earlier. The wet year used for simulation usually results in slightly higher estimate of the magnitude of short-term sediment deposition downstream of the dam.

In all four runs, the reservoir draw-down with the low-level outlet was started on July 1^{st}, during the base-flow season. The discharge record used for the period of July 1 to September 30 following the draw-down was the discharge record between 7/1/1975 and 9/30/1975 for all the runs, because the variations in base flow for different years was minor. The complete hydrologic series for each run is given in Table 7.

Table 7. Hydrologic series used for the four runs

Time since reservoir draw-down	0–6 months	7–18 months	19–30 months	31–36 months
Runs 1 and 2	7/1/1975 – 9/30/1975 (base flow)	10/1/1990– 9/30/1991 (dry year)	10/1/1975 – 9/30/1976 (average year)	10/1/1971– 3/30/1970 (wet year)
Runs 3 and 4		10/1/197 – 9/30/1970 (wet year)		10/1/199 – 3/30/1991 (dry year)

Run 1

The relationship between discharge and reservoir water surface elevation with the control gate fully open is shown in Figure 22. This relationship was used to define the water surface level upstream of Iron Gate Dam during the simulation. The discharge series starts with the base flow as discussed earlier and followed with dry – average – wet water years. Simulation results, shown in Figure 23, indicate that flow through the outlet would not result in any sediment deposition downstream of the dam. In time, sediment in the upstream portion of the reservoir would be eroded and transported downstream, and there would be a sediment deposit within about 1 mile upstream of the dam, which would not be transported downstream of the dam. This deposition can be viewed as a quasi-equilibrium deposit in association with flow and sediment passing through the low-level outlet. This quasi-equilibrium was reached following the high flow event, or at about 1 year after the gate was open.

Run 2

In Run 2 we assumed that the removal of the dam would take 6 months to complete (i.e., the flow and sediment would pass through the outlet for the first 6 months of simulation and then through the main channel once the dam was removed). This run used a dry water year following the three-month base-flow series. Results of the simulation, shown in Figure 24, indicate that there would be a maximum of less than 4 ft of sediment deposition downstream of the dam and upstream of RM 183. After two weeks, the maximum sediment deposition decreases to less than 2 ft. Almost all the sediment deposit disappears in 6 month following the final stage of the dam removal. No sediment deposition is predicted downstream of RM 183. Again, the prediction of this simulation represents the worst-case scenario and it can be expected that the sediment deposition downstream of Iron Gate Dam would be significantly smaller following the removal of the dams. This result should not significantly increase flooding, because if flow increased the sediment would be quickly transported downstream.

Run 3
Run 3 is identical to Run 1 except that the hydrologic series used in the modeling was three months of base flow followed by a wet, an average, and a dry year. Results for Run 3 are given in Figure 25. As a result of higher discharge within the first year following the reservoir draw-down, Run 3 flushed sediment more quickly than in Run 1. The final deposition with flushing from the low-level outlet is very similar to that of Run 1.

Run 4
Run 4 is identical to Run 2 except that the hydrologic series used in the modeling included three months of base flow followed by a wet water year. Results for Run 4 are given in Figure 26. The magnitude of sediment deposition is similar to that in Run 2 (i.e., less than 4 ft), but the duration that the sediment deposit persisted was much shorter than in Run 2. After 4 weeks, there is less than a foot of sediment remaining at RM 186, and none upstream.

6 Discussion and Preliminary Conclusions

Based on the shear velocity vs. settling velocity calculation and the DREAM-1 simulation under the worst-case assumptions, it appears that following the removal of J.C. Boyle, Copco, and Iron Gate dams, sediment deposition downstream of Iron Gate Dam would be minimal. In particular, under realistic dam removal scenarios (Runs 2 and 4) using the worst-case assumptions, the maximum thickness of sediment deposition downstream of the dam would be less than 4 ft. The deposit would be quickly transported downstream and the overall duration of impact would range between 1 month for a wet year and about 6 months for a dry year.

Results of this simulation are based on available information using built-in safety factors for various parameters, and the results should be viewed as the worst-case scenario and treated as preliminary. Better characterization of reservoir sediment deposits, both in their spatial distribution and grain size distribution, would help increase the confidence level of the assessment, which will likely result in significantly reduced magnitude of sediment deposit within the main channel downstream of the dam.

In addition, the model is one-dimensional and employed a very coarse grid system (1 mile). Because of the limitations of a one-dimensional model, sediment deposition in areas such as deep pools and channel margins cannot be assessed. It can be expected that there would be sediment deposition in pools during low-flow periods, which would be flushed out during high-flow events.

While we did not specifically model flood risk, the modeling indicates that if there is an increased risk, it would be short-lived. If a high recurrence interval flow does occur it might results in an increased stage height in the river, but the high flow would act to rapidly transport sediment, possibly during the rising stage of the flood, thereby minimizing the time period of elevated stage.

One of the major potential biological impacts of dam removal could result from increased suspended sediment concentrations and turbidity levels. Modeling results do not include suspended sediment concentrations. More field data, preferably collected during a reservoir draw-down experiment, would be needed to derive parameters that could be used to quantify the reservoir erosion process and allow credible modeling of suspended sediment concentration following dam removal.

We also offer the following discussions and suggestions.

1. During and soon after the removal of Copco Dam, keep Iron Gate Reservoir at a level to maintain the turbidity level downstream of the Iron Gate Dam below the maximum acceptable level.

2. Design and conduct a comprehensive data collection program during the removal of Copco Dam. Because sediment in Copco Reservoir is likely similar to that in Iron Gate Reservoir, the suspended sediment and turbidity level upstream of Iron Gate Reservoir during the removal of Copco Dam would provide an excellent indication of the suspended sediment condition downstream of Iron Gate Dam following its removal, if it were removed under similar hydrological conditions. The data collected in the area of Copco Reservoir could be used to quantify the parameters needed for an accurate simulation of the reservoir erosion process in Iron Gate Reservoir, assuming that the characteristics of sediment deposit between the two reservoirs are similar.

3. According to the available information on the low-level outlet on Iron Gate Dam, it would be possible to use the outlet to control the water surface level in Iron Gate Reservoir by partially opening the gate. During Iron Gate Dam's deconstruction, the gate should be operated so that the suspended sediment and turbidity are at the maximum acceptable level, while keeping the water surface elevation in Iron Gate Reservoir at a safe elevation below the excavated surface of Iron Gate Dam. This would help to flush the maximum amount of sediment while minimizing environmental impacts during the dam removal process.

   It must be noted, however, that there are two potential problems with this strategy: (1) as the dam deconstruction continues, the maximum water surface level allowed for such operation would decrease, and thus, it will become more difficult to control water release during the later stages of the drawdown; and (2) the amount of sediment that can be flushed out of the reservoir within a 6-month period is minimal. Assuming a continuous suspended sediment concentration of 500 ppm, which is on the high side for allowable chronic suspended sediment concentration to avoid salmonid mortality (Newcombe and Jensen 1996), the maximum amount of sediment that could be flushed out of the reservoir is only 307,000 to 528,000 yd^3 for the hydrologic conditions tested, as shown in Figure 27.

   A better strategy would be to minimize the time period that the low-level outlet has to be used for flushing, and to plan the construction work so that the dam excavation would be completed before and near the high flow season.

Acknowledgments: Most of the information and previous reports used in this analysis were assembled by Steve Rothert of American Rivers, who also provided detailed guidance for the modeling and careful review of an early draft. The project wouldn't have progressed smoothly without Steve's personal attention. Discussions with Brian Cluer of NOAA Fisheries, Bill Dietrich of UC Berkeley, and Tim Randle of the Bureau of Reclamation before and during this analysis are gratefully acknowledged. The useful comments from Brian Cluer, Thomas Lisle, Gordon Grant, Dennis Gathard, Tim Randle, and Laura Wildman have been incorporated into the report.

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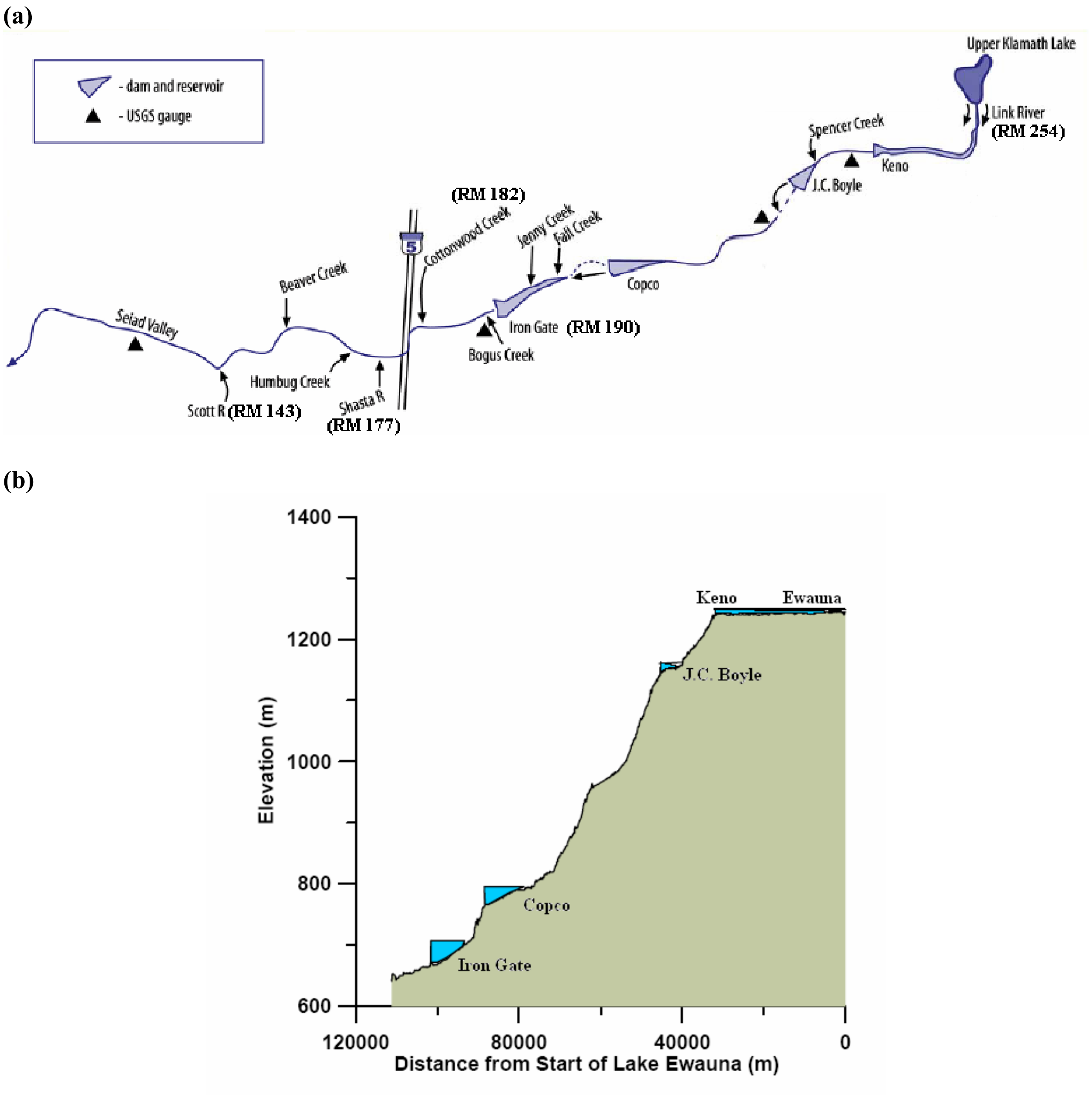

Figure 1. Reservoirs and dams on the Klamath River: (a) modified from PacifiCorp (2003); and (b) modified from Eilers and Gubala (2003)

Figure 2. Iron Gate Dam on the Klamath River, California, looking upstream.

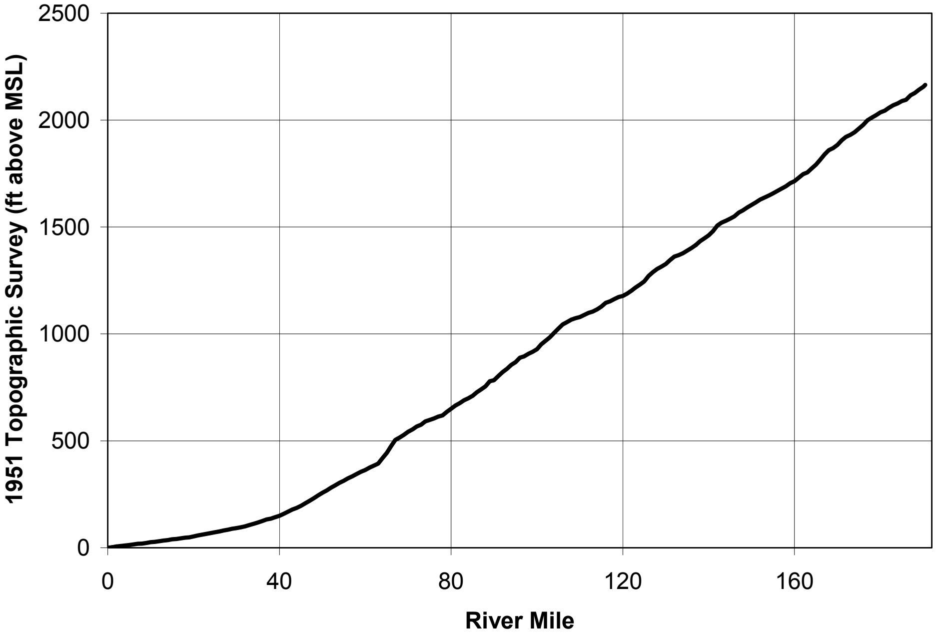

Figure 3. Longitudinal profile of the Klamath River downstream of Iron Gate Dam, based on 1951 topographic survey presented in Ayres Associates (1999)

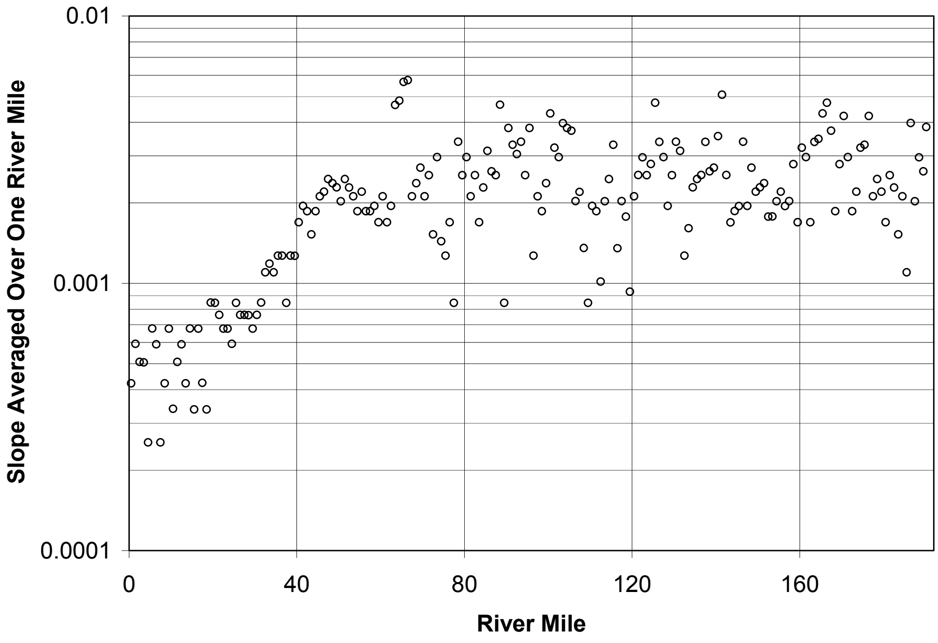

Figure 4. Channel gradient averaged over one-mile distances in the Klamath River downstream of the Iron Gate Dam, based on 1951 topographic survey presented in Ayres Associates (1999)

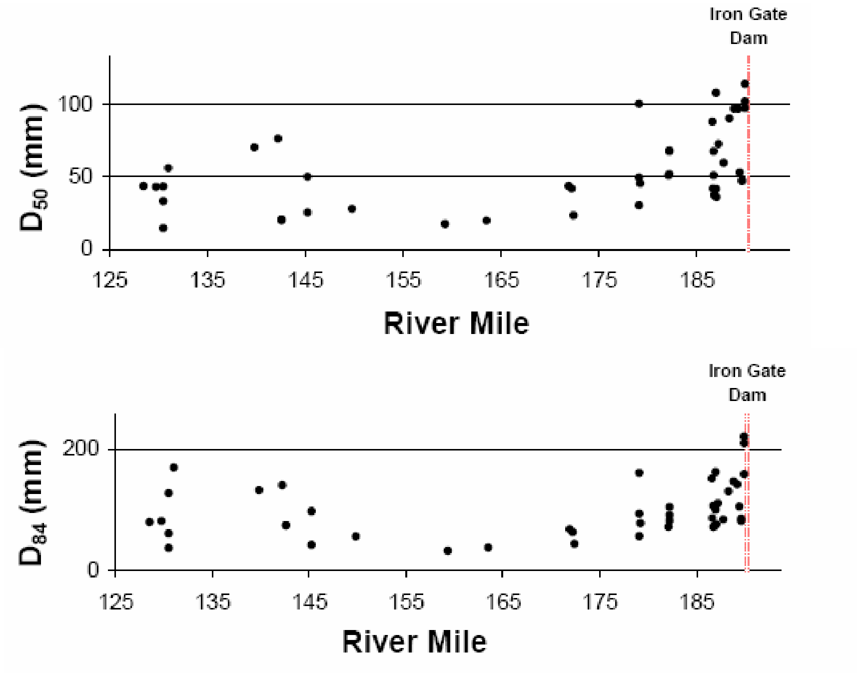

Figure 5. Characteristic grain sizes downstream of Iron Gate Dam between RM 125 and RM 190, based on surface pebble counts by PacifiCorp. Diagrams modified from PacifiCorp (2003)

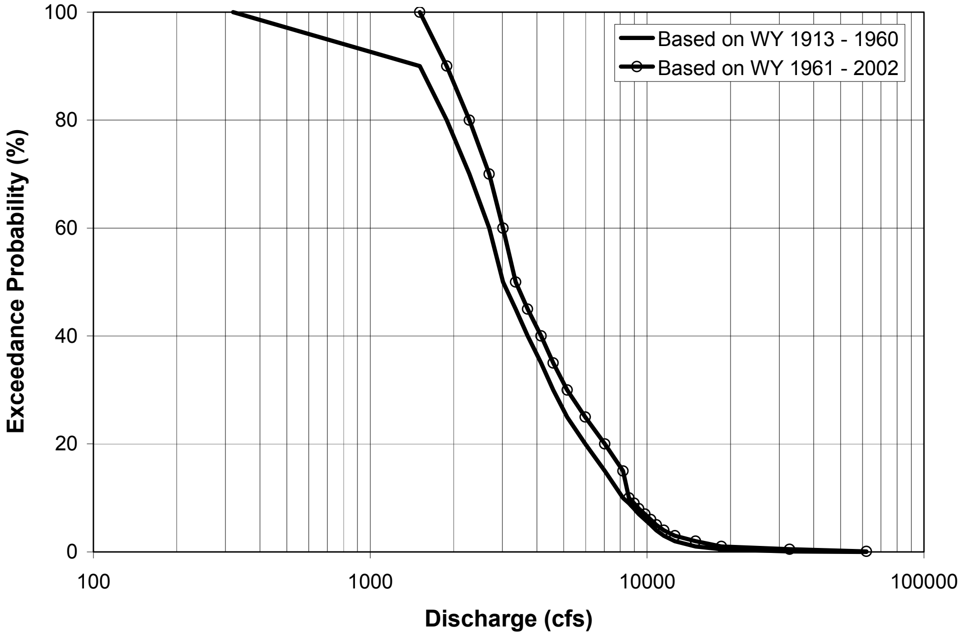

Figure 6. Klamath River flow duration curves near Seiad Valley for the periods of WY 1913 – 1960 and WY 1961 – 2002, based on daily average discharge record at USGS station 11520500

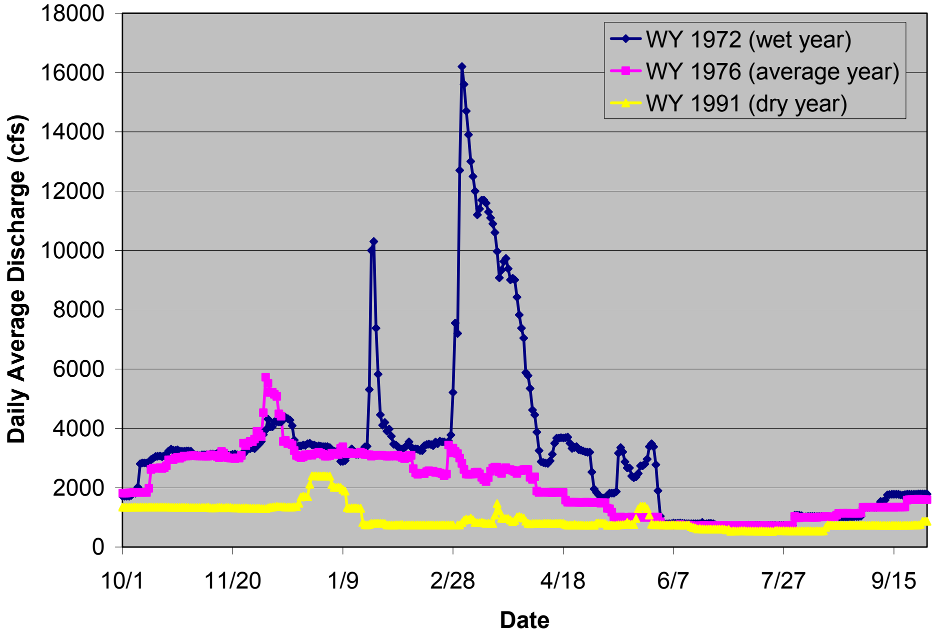

Figure 7. Daily discharge record for three typical years representing wet, average and dry conditions at USGS #11516530 Klamath River below Iron Gate Dam, CA

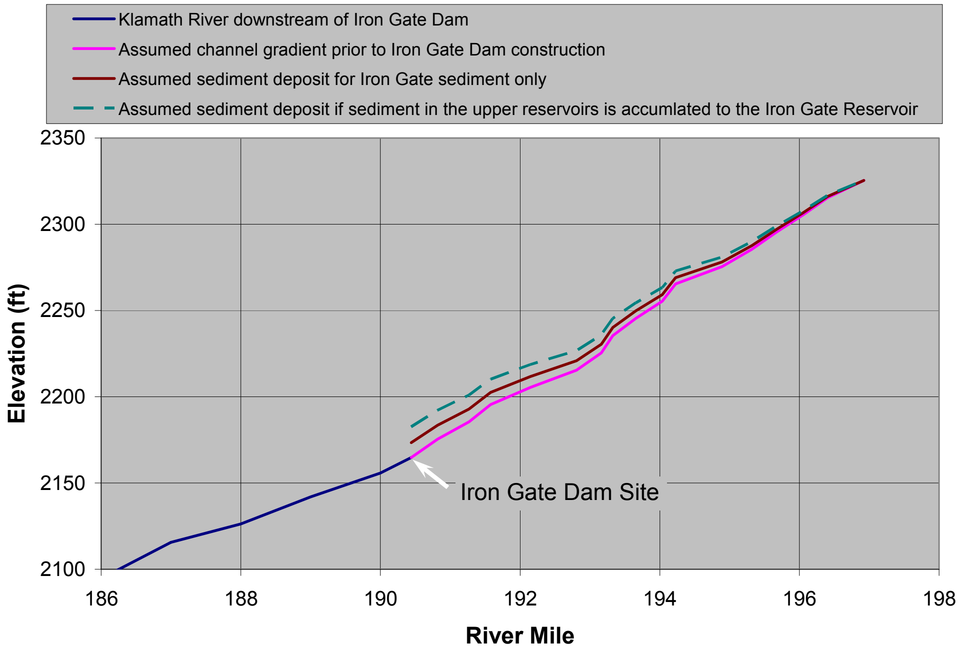

Figure 8. Assumed longitudinal distribution of sediment deposit in the Iron Gate Reservoir. The average depositional thickness in this diagram is 10 times of the average thickness if the sediment deposit is spatially distributed uniformly.

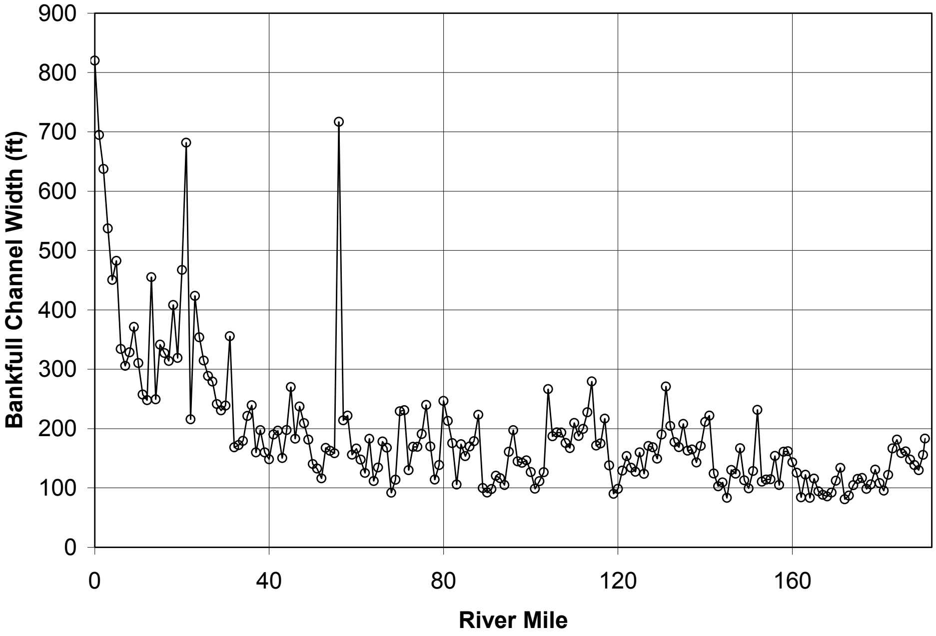

Figure 9. Bankfull channel width along the Klamath River downstream of Iron Gate Dam. The widths were first read from the 1:7,500 scale aerial photographs and then interpolated to 1-mile spacing for dam removal simulation.

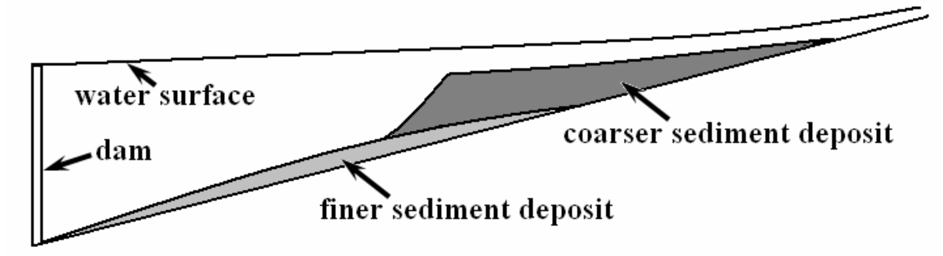

Figure 10. Sketch demonstrating typical longitudinal distribution of reservoir sediment deposit

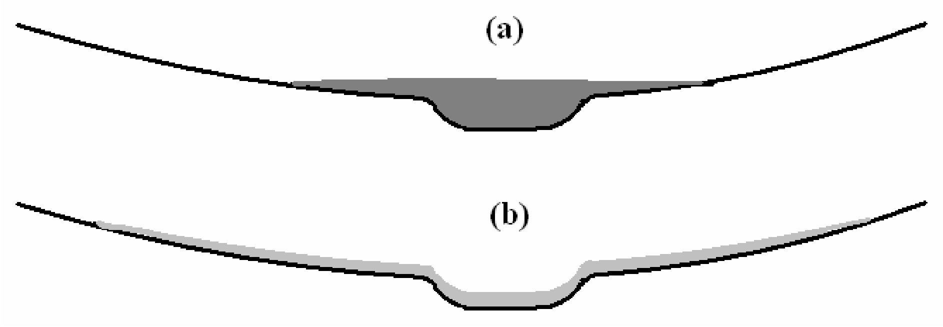

Figure 11. Sketch demonstrating the lateral distribution of reservoir sediment deposit: (a) coarse sediment deposit; (b) fine sediment deposit

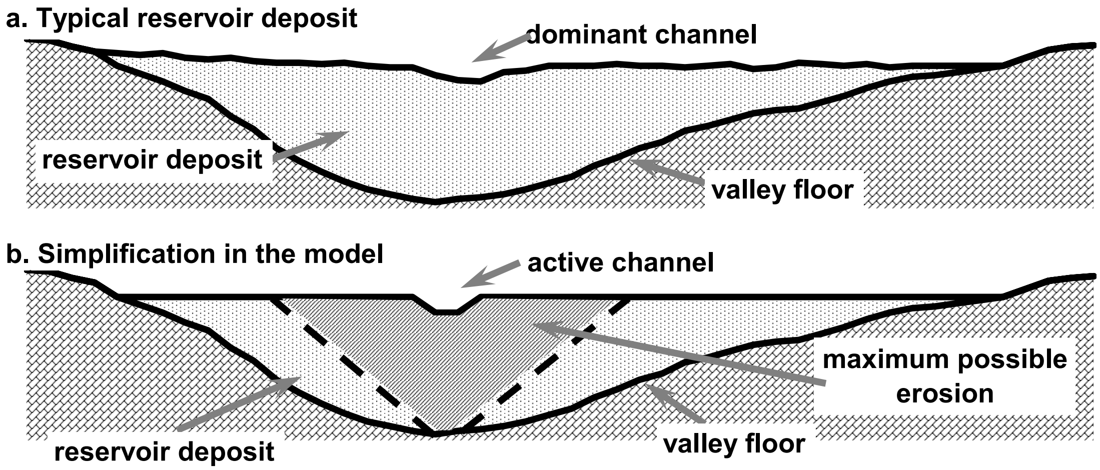

Figure 12. Assumptions in the erosion of reservoir deposit, modified from Cui et al. (in press [a])

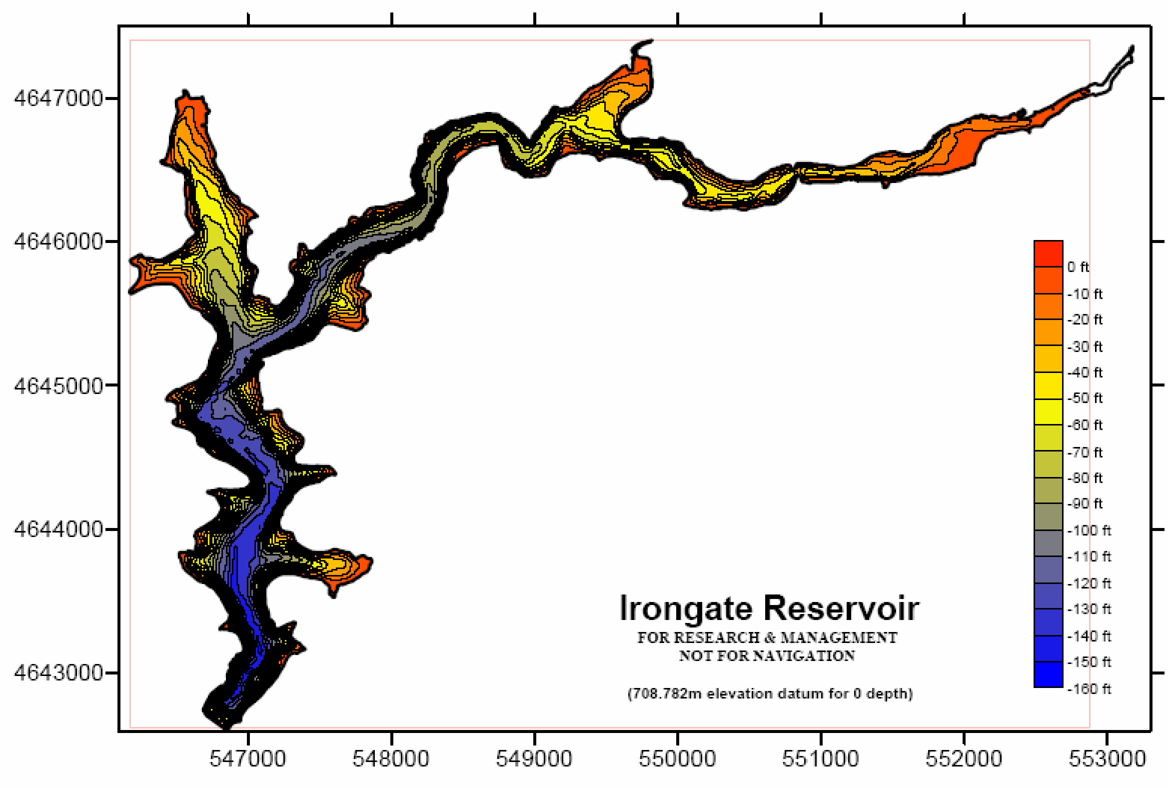

Figure 13. Bathymetry in the Iron Gate Reservoir (Eilers and Gubala, 2003), where the north and east are in meters

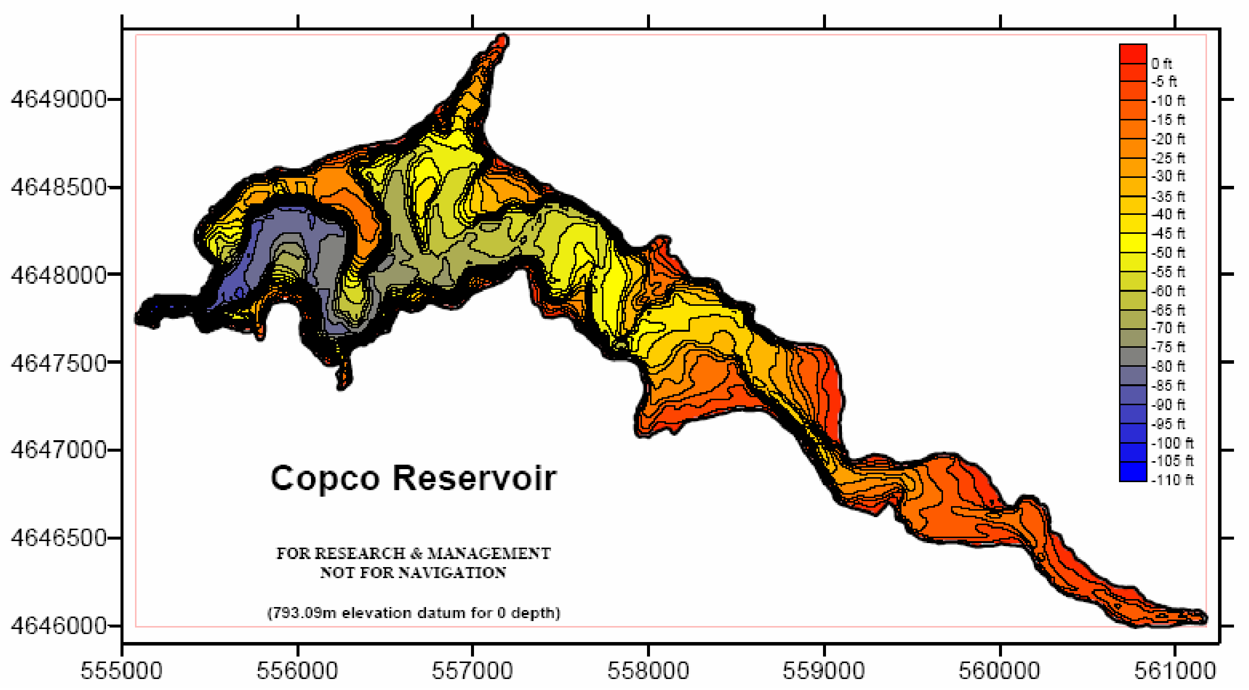

Figure 14. Bathymetry in the Copco Reservoir (Eilers and Gubala, 2003), where the north and east are in meters

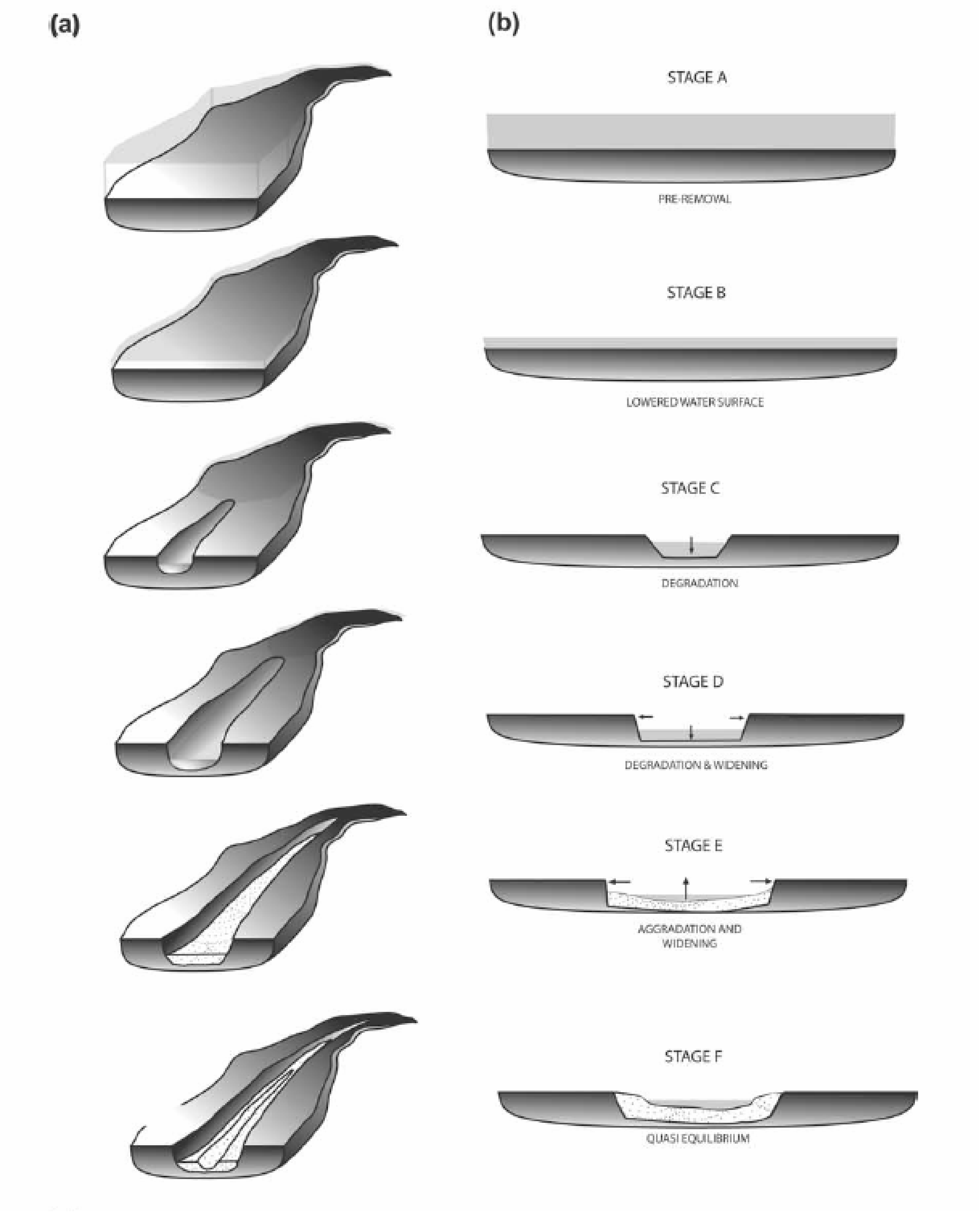

Figure 15. The conceptual model of Doyle et al. (2003) on reservoir erosion, indicating that the erosional width of the reservoir deposit will not be significantly wider than the final quasi-equilibrium channel. See Doyle et al. (2003) for details.

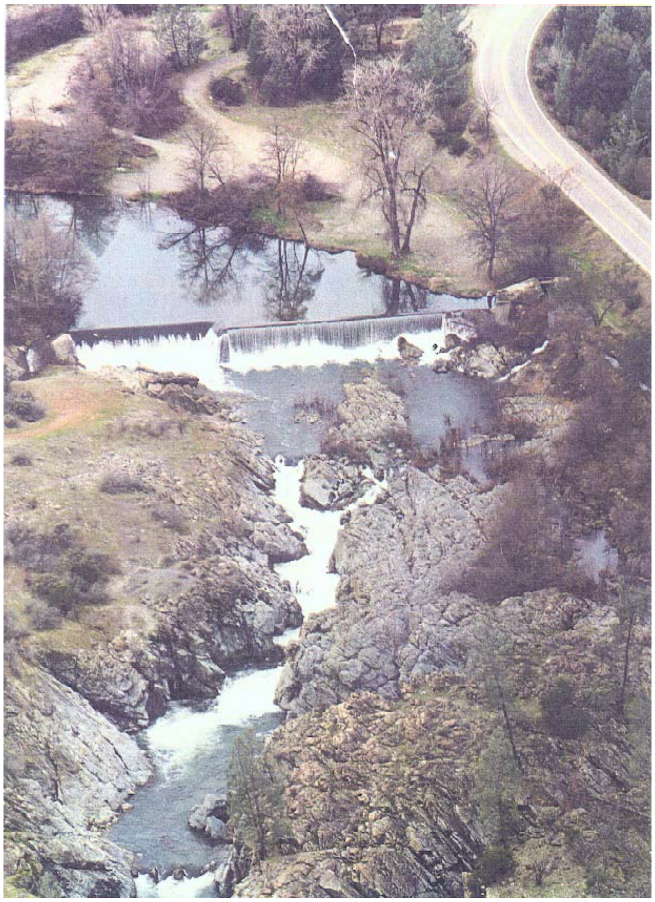

Figure 16. Clear Creek, California. Top: Saeltzer Dam, removed in 2000, courtesy of Geoff Fricker. Bottom: Former Saeltzer Reservoir area in 2003, courtesy of Peter Miller. Channel width in the former reservoir area is approximately 100 ft, similar to that in the downstream stable fluvial reach.

Figure 17. Town Creek, California. Top left: Town Creek Dam, collapsed in early 1980s during a storm event. Top right: Channel eroded in the former Town Creek Reservoir. Bottom: Town Creek downstream of the collapsed dam in the stable fluvial reach. All photographs were taken in 2001. Visual observations indicate that channel width within the former reservoir area is comparable to that in the downstream stable fluvial reach.

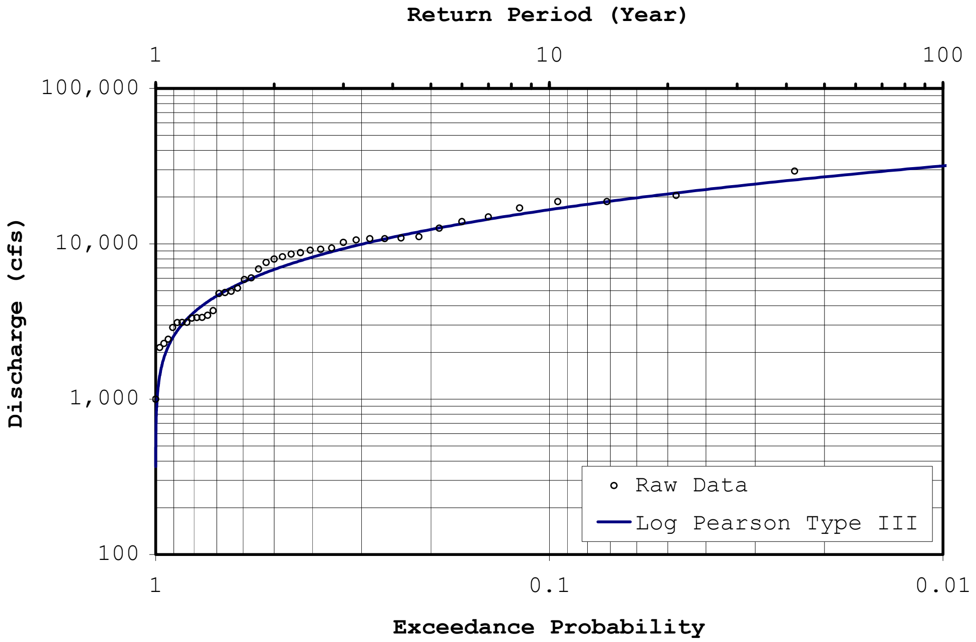

Figure 18. Peak flow downstream of Iron Gate Dam, based on USGS #11516530 Klamath River below Iron Gate Dam station peak flow record between WY 1961 and 2002

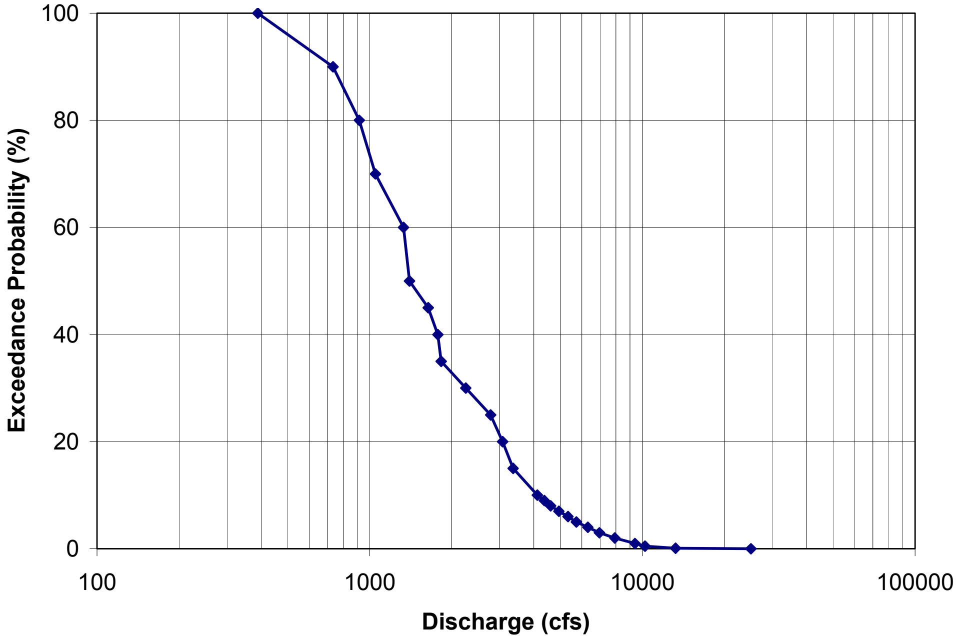

Figure 19. Flow duration curve downstream of the Iron Gate Dam, based on USGS #11516530 Klamath River below Iron Gate Dam station daily average discharge record between WY 1961 and 2002

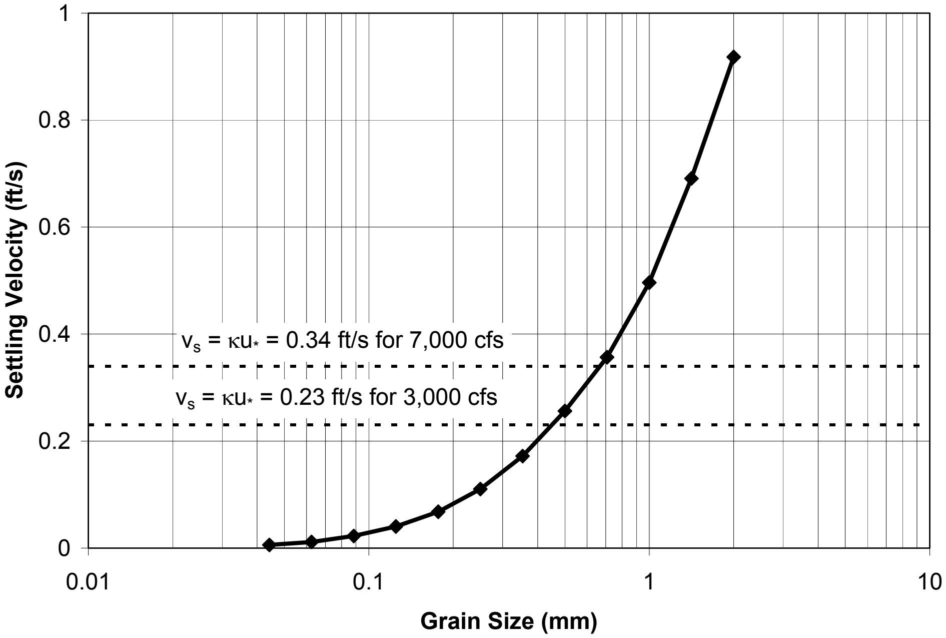

Figure 20. Particle settling velocity calculated with the procedure of Dietrich (1982), assuming a specific density of 2.65

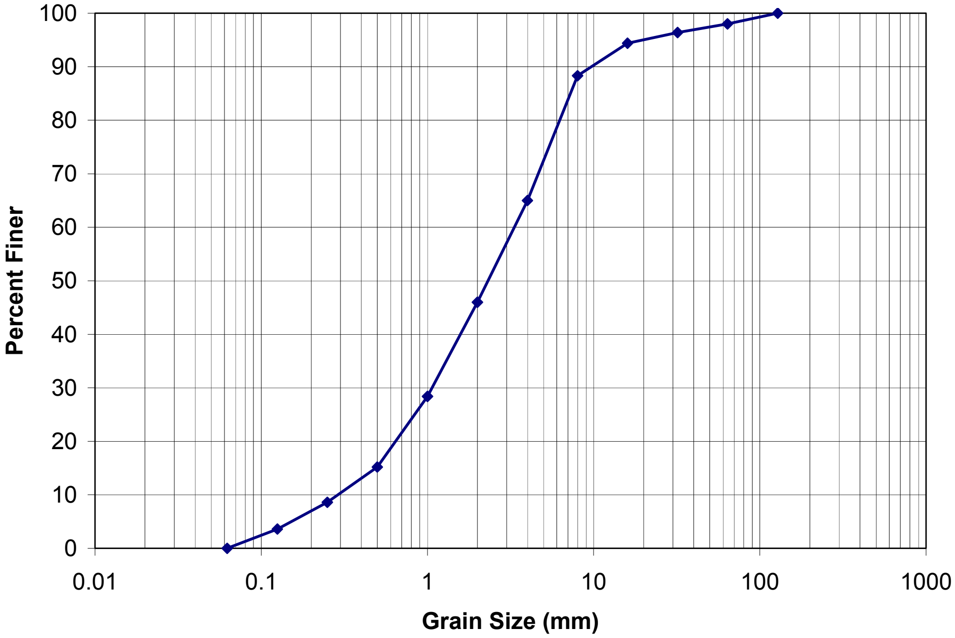

Figure 21. Assumed grain size distribution for sand and coarser in the reservoir deposit. This grain size distribution is probably coarser than the sand and coarser portion of the actual reservoir deposit

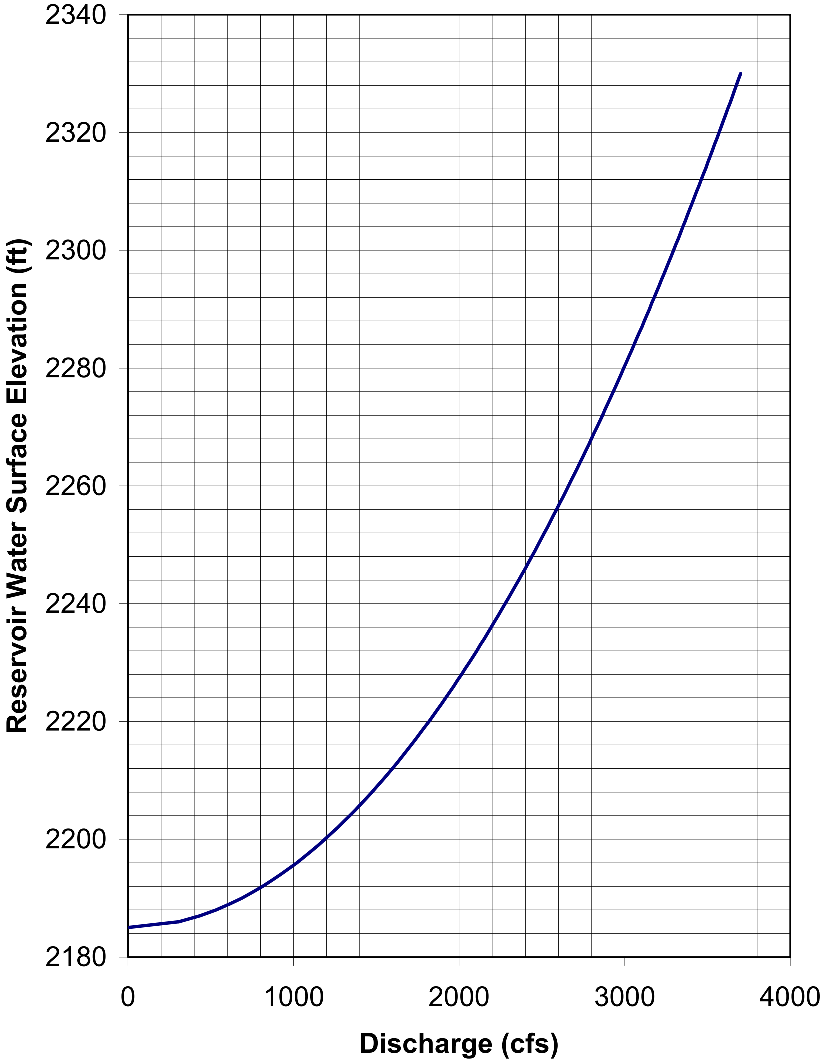

Figure 22. Discharge – Reservoir Water Surface Elevation relation for the low level outlet in the Iron Gate Dam.

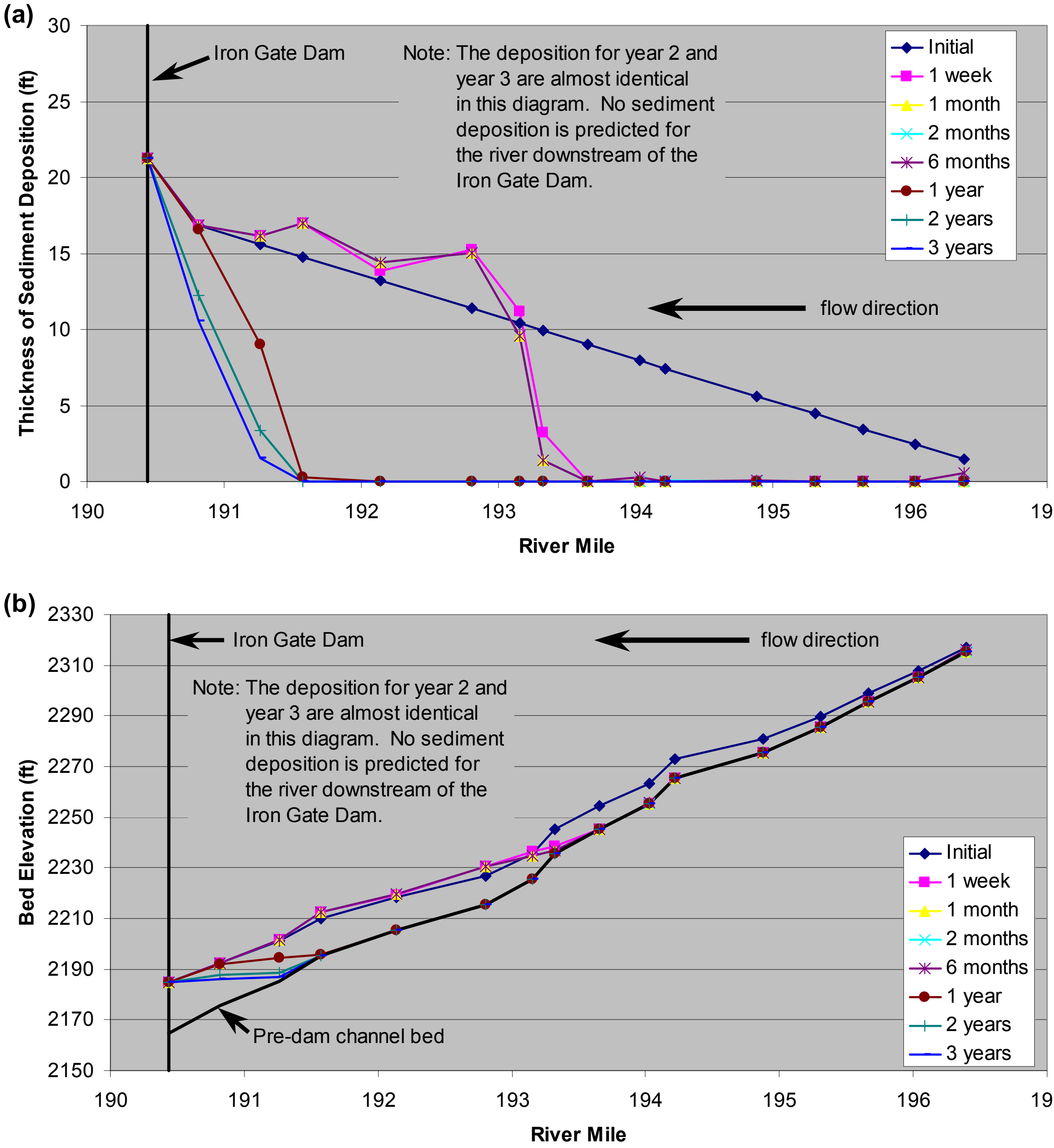

Figure 23. The predicted thickness of sediment deposition downstream of the Iron Gate Dam for Run 1. (a) Thickness of sediment deposition; and (b) bed elevation. The hydrologic series is three months of base flow followed by a dry, an average, and a wet year. All the other parameters are under the worst-case scenario as discussed in Section 5.3.

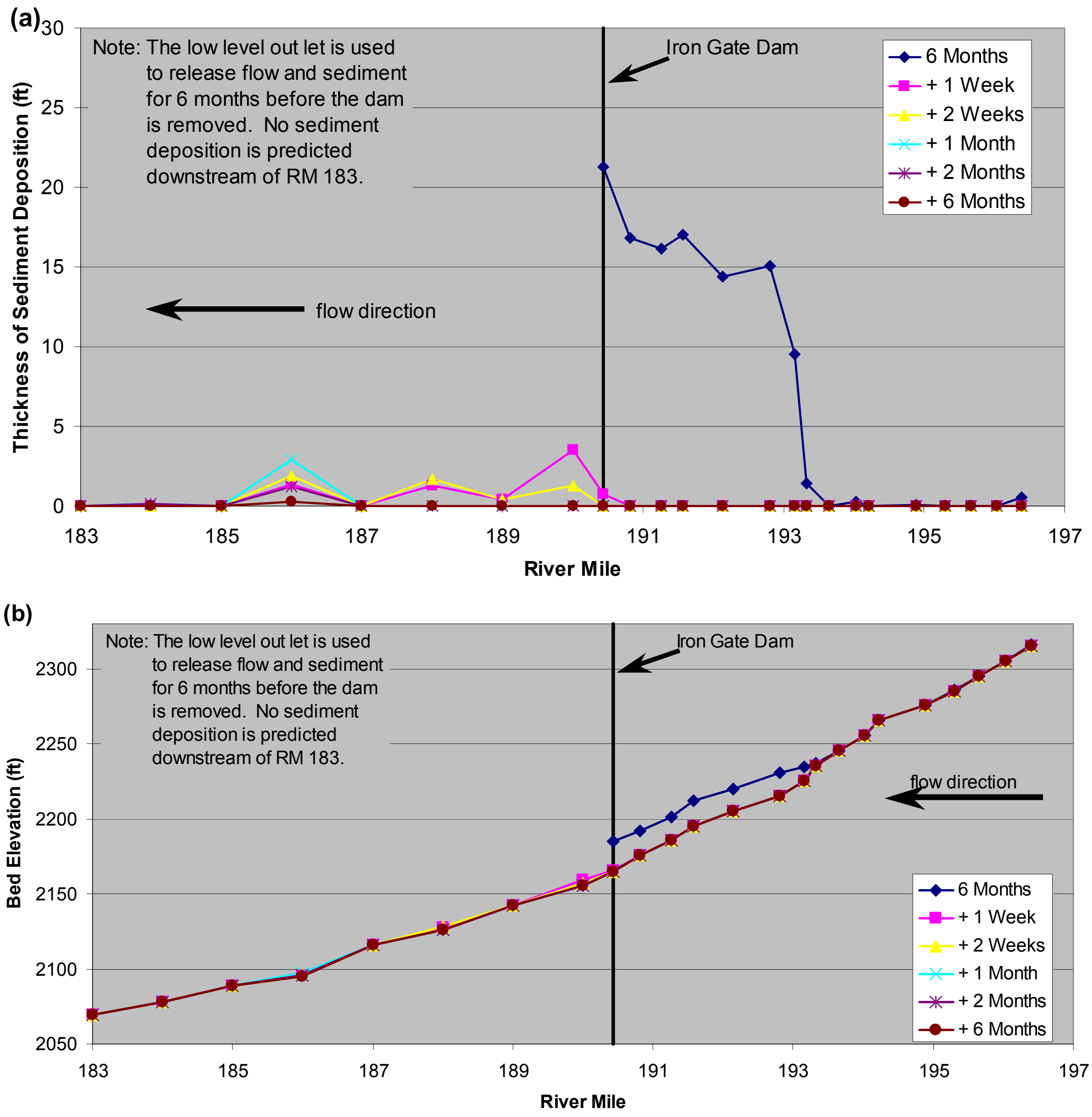

Figure 24. The predicted thickness of sediment deposition downstream of the Iron Gate Dam for Run 2. (a) Thickness of sediment deposition; and (b) bed elevation. The hydrologic series is three months of base flow followed with a dry year. All the other parameters are under the worst-case scenario identical to Run 1 and as discussed in Section 5.3.

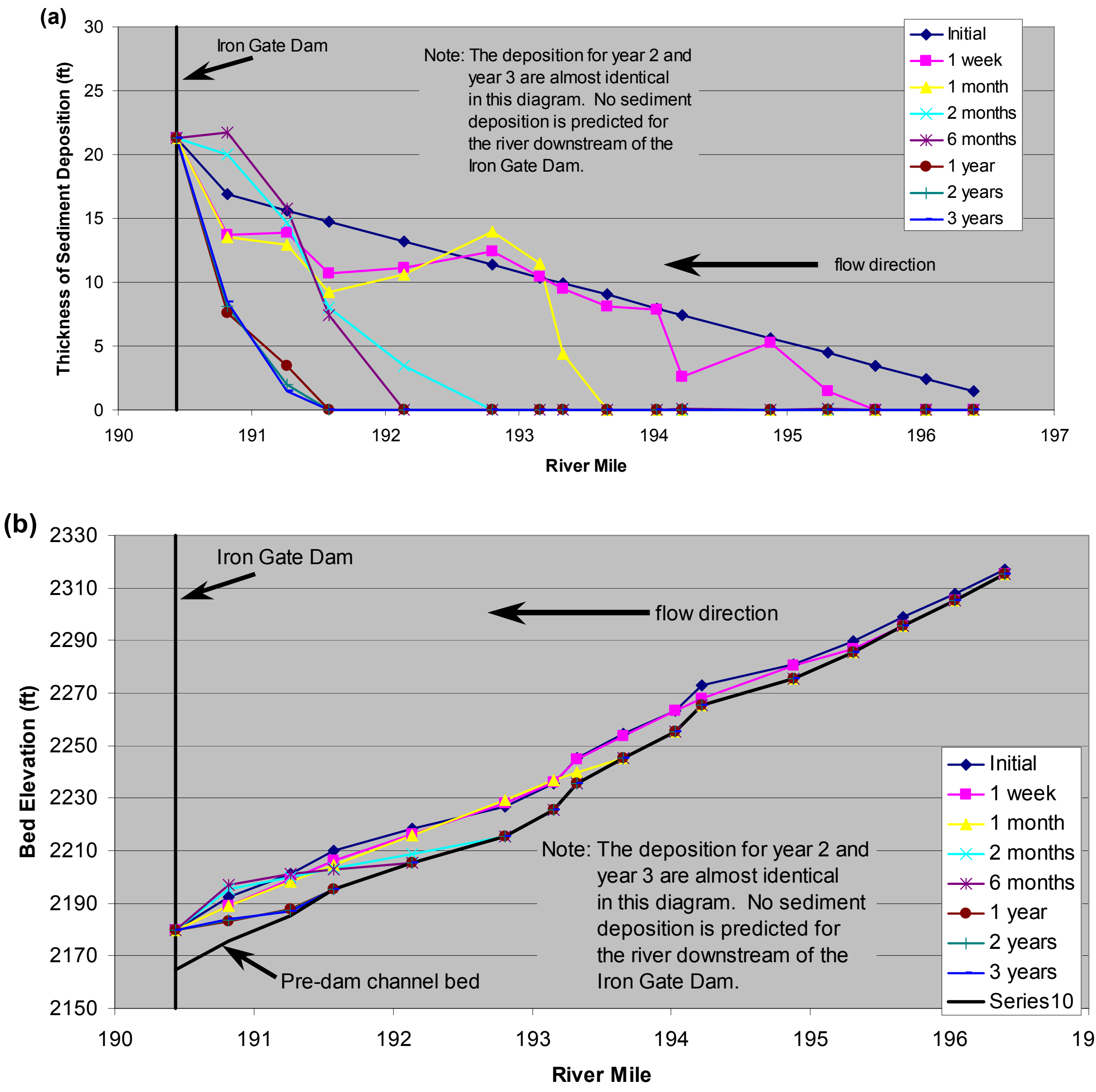

Figure 25. The predicted thickness of sediment deposition downstream of the Iron Gate Dam for Run 3. (a) Thickness of sediment deposition; and (b) bed elevation. The hydrologic series is three months of base flow followed by a wet, an average, and a dry year. All the other parameters are under the worst-case scenario identical to Runs 1 and 2 and as discussed in Section 5.3.

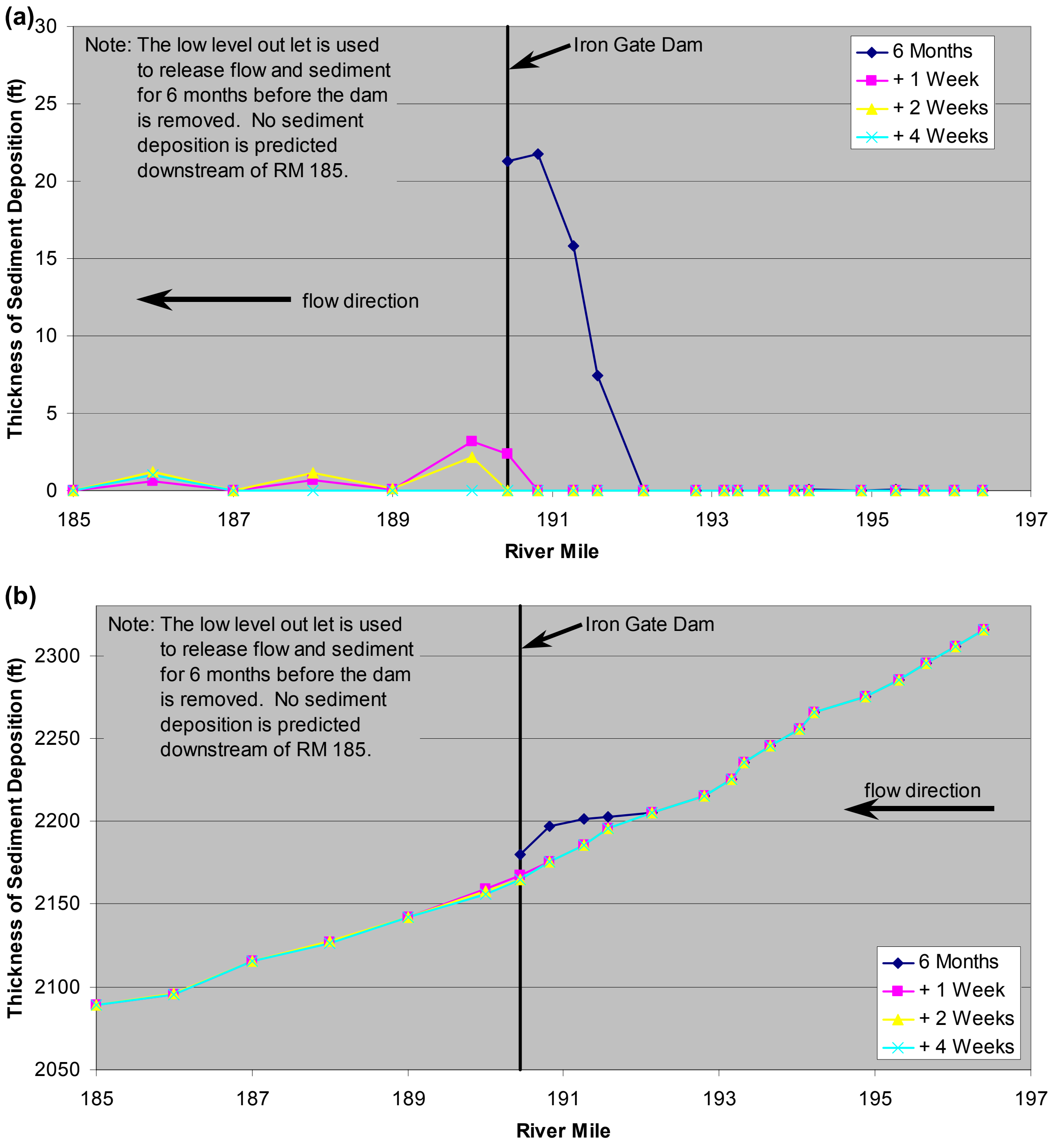

Figure 26. The predicted thickness of sediment deposition downstream of the Iron Gate Dam for Run 4. (a) Thickness of sediment deposition; and (b) bed elevation. The hydrologic series is three months of base flow followed with a wet year. All the other parameters are under the worst-case scenario identical to Runs 1 through3 and as discussed in Section 5.3.

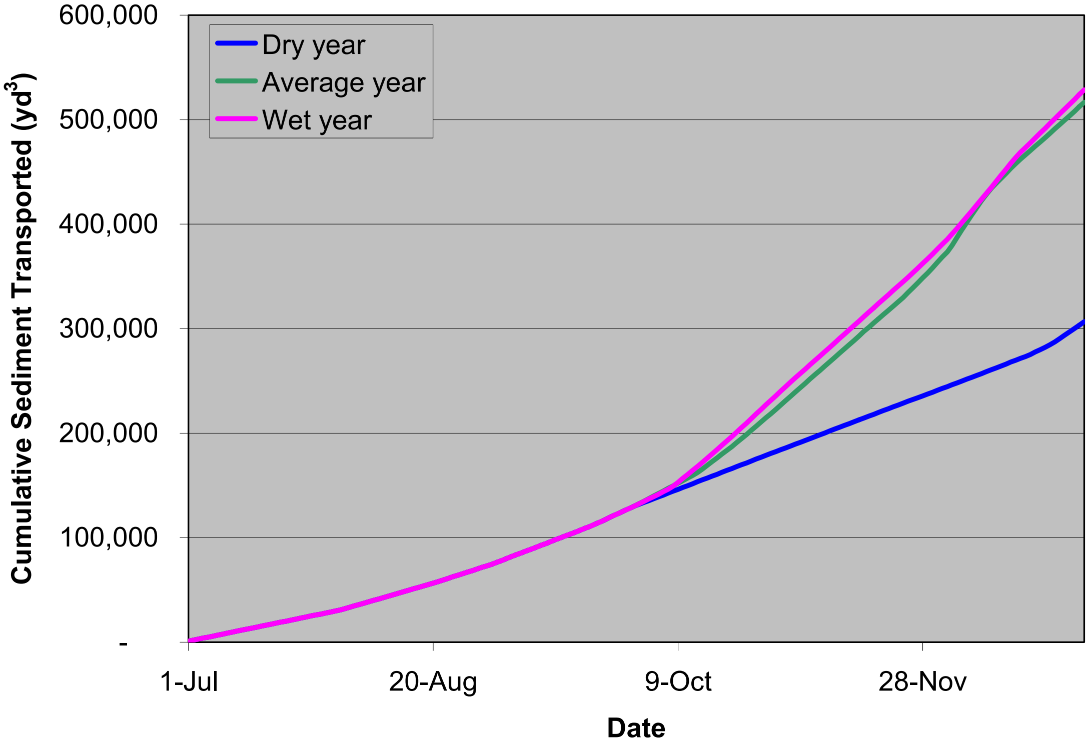

Figure 27. The amount of sediment that can be flushed out of Iron Gate Reservoir with the low level outlet in a 6 months period, assuming a constant suspended sediment concentration of 500 ppm, and a porosity of 0.45.